AFRL-AFOSR-VA-TR-2016-0063

High-Resolution, Low-Cost Spectrometer-on-Chip

Christophe Peroz
ABEAM TECHNOLOGIES INC.

01/02/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
12/27/2014	Final report	09/30/2012 - 09/29/2014

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER** FA9550-12C-0077
HIGH-RESOLUTION, LOW-COST SPECTROMETERS-ON-CHIP	**5b. GRANT NUMBER**
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Dr. C. Peroz, Dr. S. Babin, Dr. S. Cabrini, Dr. V. Yankov, G. Calafiore, S. Dhuey	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Abeam Technologies, Inc. 22290 Foothill Blvd., St.2 Hayward, CA 94541	0002AG
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** USAR AFRL
US Air Force, AFRL AF Office of Scientific Research 875 North Randolph Street, Rm 3112 Arlington, VA 22203	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** 0002AE

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A novel class of low-cost and high resolution spectrometer-on-chips has been developed that are suitable for numerous laser-monitoring applications. The technology is based on the integration of digital planar holograms and a full optical circuitry on the same photonic chip. The prototypes are fabricated at a low-cost by nanoimprint lithography and are packed into the size of a USB key. Nano-spectrometers with a resolution down to 0.5 nm and a spectral range up to 229 nm were successfully demonstrated. The original concept of an on-chip spectrometer integrated into commercial image sensors was demonstrated and opens the route to numerous applications. Our miniaturized spectrometers are defining the state-of-the-art for on-chip spectroscopy, as well as in terms of spectral resolution and bandwidth than for their miniaturized size.

15. SUBJECT TERMS
spectrometer, nanofabrication, electron beam lithography, nanoimprint lithography

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** S. Babin
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		19	**19b. TELEPHONE NUMBER** *(Include area code)* (510) 415 6032

Reset

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

HIGH-RESOLUTION, LOW-COST SPECTROMETERS-ON-CHIP

STTR project Phase II – Final Report

30 September 2012 – 29 September 2014

Abstract: A novel class of low-cost and high resolution spectrometer-on-chips has been developed that are suitable for numerous laser-monitoring applications. The technology is based on the integration of digital planar holograms and a full optical circuitry on the same photonic chip. The prototypes are fabricated at a low-cost by nanoimprint lithography and are packed into the size of a USB key. Nano-spectrometers with a resolution down to 0.5 nm and a spectral range up to 229 nm were successfully demonstrated. The original concept of an on-chip spectrometer integrated into commercial image sensors was demonstrated and opens the route to numerous applications. Our miniaturized spectrometers are defining the state-of-the-art for on-chip spectroscopy, as well as in terms of spectral resolution and bandwidth than for their miniaturized size.

The main accomplishments in Phase II can be summarized as follows:

–1. Monolithically integrated several planar holograms with a full optical circuitry and optimized the coupling efficiency.

--2. Demonstrated a spectrometer-on-chip for the visible and near infrared range.

--3. Replicated DPH chips at a low-cost by nanoimprint lithography.

--4. Optically validated the devices and compared them to commercial systems.

--5. Prototyped a whole spectrometer system with a small footprint package.

--6. Demonstrated the novel concept of an on-chip spectrometer integrated with commercial image sensors.

I – Monolithic integration of DPHs with a full optical circuitry

The monolithic integration of digital planar holograms (DPH) into a planar lightwave circuit is necessary in order to build up broadband and create an efficient spectrometer-on-chip

a) Simulation, Design :

We have simulated and designed a spectrometer-on-chip integrating DPHs and a full optical circuitry on the same chip (Fig. 1). Multiple DPHs has been connected with single mode ridge waveguides (RWG), light splitters, polarizers and tapers. Each DPH is designed to work for one specific spectral bandwidth and each individual optical element has been optimized by successive iterations between the design, fabrication and measurements. As an example, Figure 2 shows the design and simulation of the light splitter and mode converters. Specific test-chips (Figure 3) were used to measure the main characteristics of the optical circuitry by varying the widths, curvature radius and height in order to optimize the performance of each optical component. The contribution of the material losses and vertical edge roughness to the propagation losses in the RWG was optimized down to 2.5 dB/cm and 6.0 dB/cm, respectively. The input coupling efficiency between the input RWG and the optical fiber reached around 61% by using an inverted taper, which is three times higher than when using a regular taper. Three different splitters (directional coupler, Multi-Mode Interferometer (MMI) and Y-splitter) were compared. Initial results seem to show that the most efficient geometry is the directional coupler with almost no losses, and the Y-splitter with around 11% losses, while the MMI exhibited about 50% loss.

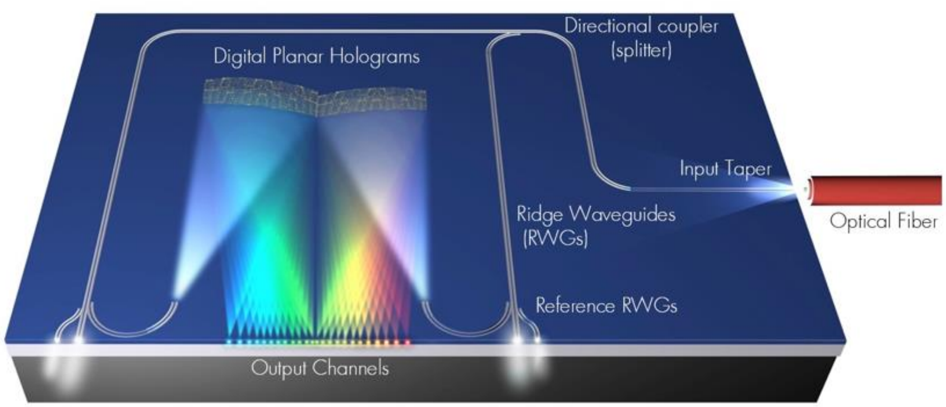

Figure 1: Schematics of one spectrometer chip integrating two holograms.

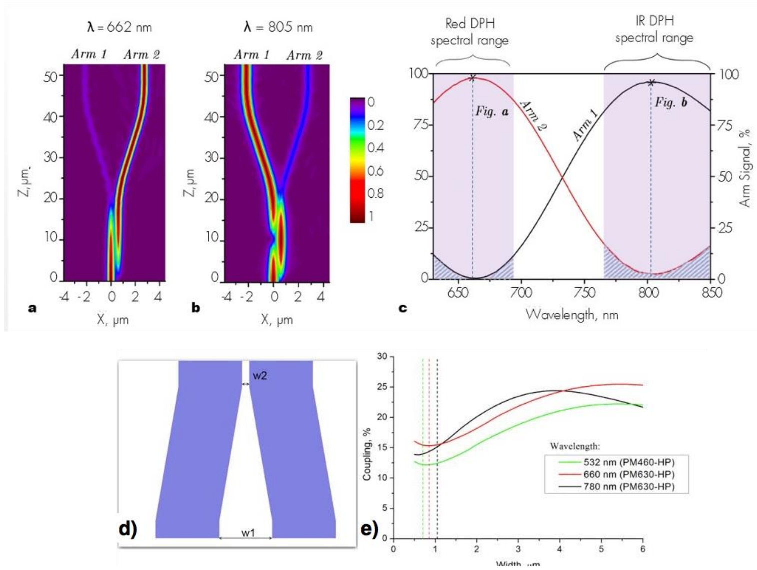

Figure 2: Simulation of integrated light splitter. Optical responses of one directional light coupler for input wavelengths of (a) 662 nm and (b) 805 nm. The light that enters the splitter is guided to different waveguides according to its wavelength. This device is used to bring light to different DPHs and is the main component that enables the integration of multiple holograms and consequent spectral broadening. (c) The splitting efficiency is mapped to the function of the wavelength. b) Schematic of an input taper for the spot size converter; input fiber is connected from the bottom; b) simulation of the coupling efficiency vs. width w_1.

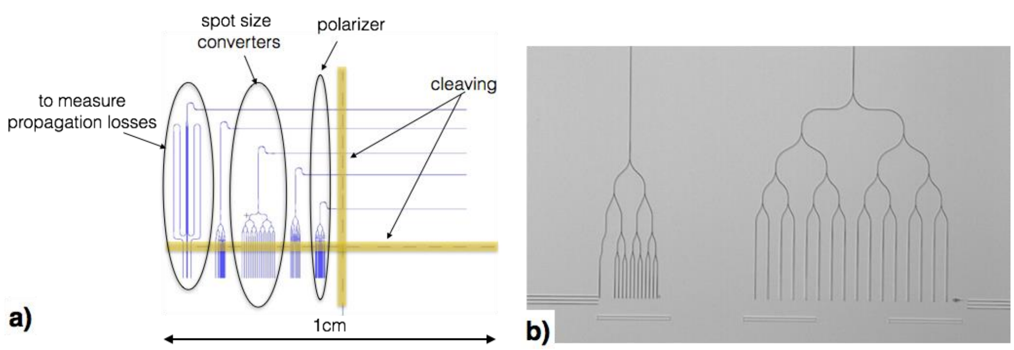

Figure 3: a) schema, b) optical picture of a test-chip.

b) Fabrication:

Fabrication of all the chips was performed using Si/SiO_2(8 µm)/Si_3N_4(160 nm) substrates, where the Si_3N_4 film is used as the waveguide core film. After patterning, a SiO_2 film is deposited as the upper cladding in order to decrease the scattering losses and increase the performance of the devices. All the prototype chips were made using Electron Beam Lithography (EBL) and reactive ion etching (RIE). **Specific nanofabrication processes were developed to ensure a high quality of the features and low edge roughness**. Spectrometer chips with one single etching depth and two etching depths (Fig. 3) were successfully fabricated. Although the fabrication of spectrometer chips with two levels is more complex, we have demonstrated that this technique decreases the losses in the optical circuitry and increases the input coupling efficiency when using inverted tapers. In total, more than 50 designs were fabricated by EBL and plasma etching in order to optimize each component of the final chips.

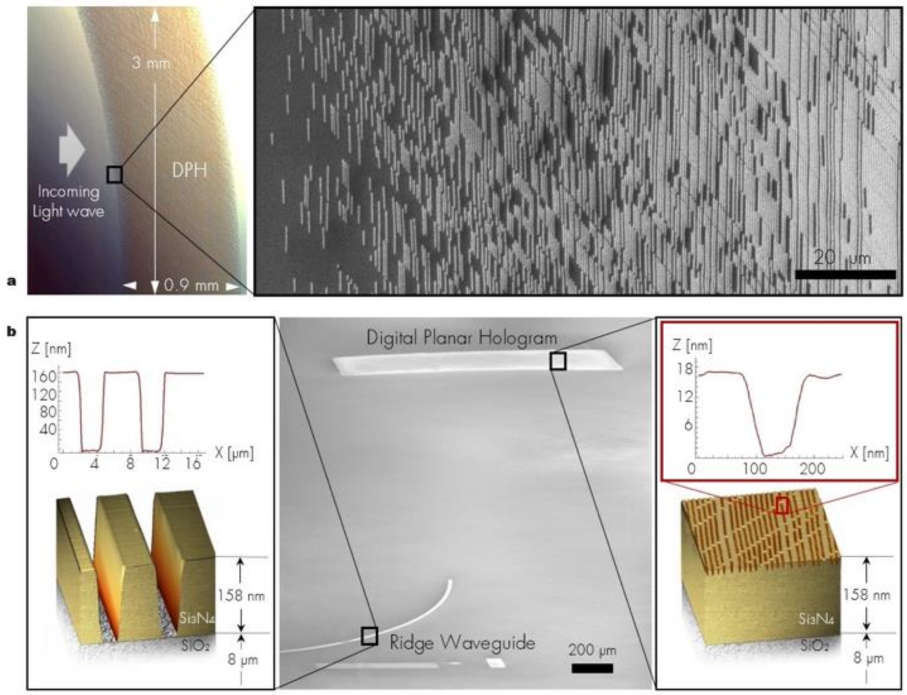

Figure 4: DPH spectrometer fabrication details. (a) Light entering the DPH goes through a smooth variation of the refractive index to avoid formation of spurious harmonics; optical microscope photo of the DPH (left), and SEM top-view of a DPH section showing the digitalized grooves embedded into the Si3N4 waveguide core (right). (b) SEM 30˚ tilted view of one planar hologram and the projecting RWG (center); the neighboring figures show the atomic force microscopy measurements of the planar hologram, etched 18 nm deep into the waveguide core (right), and the single mode RWG etched through the full Si3N4 film (left). DPH, digital planar hologram; RWG, ridge waveguide; SEM, scanning electron microscopy.

II – Spectrometer working in visible and near infra-red spectral ranges

Spectrometer chips have been fabricated and tested for a large number of different specifications (resolution, channels numbers, cross-talk) through the visible and near infra-red spectral ranges.

From the multiple tests, we draw the conclusion that there is a compromise between both structures (DPH and optical circuitry) that must be met to **reach the maximum efficiency of the spectrometer chip. The etching depth is around 15-20 nm, the number of channels is around 500, and the total bandwidth is around 100 nm.** An example of the measurements for a 506 channel spectrometer with a spectral bandwidth around 88 nm is depicted in Figure 5. The measured results are in good agreement with simulations and demonstrate that the technology is robust. The reflection of the hologram was measured to be around 9-10% (Fig. 5c). Based on these results, we have built up and characterized a spectrometer that integrates 3 DPHs with a total spectral bandwidth of 220 nm (Δλ =630-694 nm, 693-767 nm, 766-850 nm), 784 channels and an average resolution of 0.28 nm/channel.

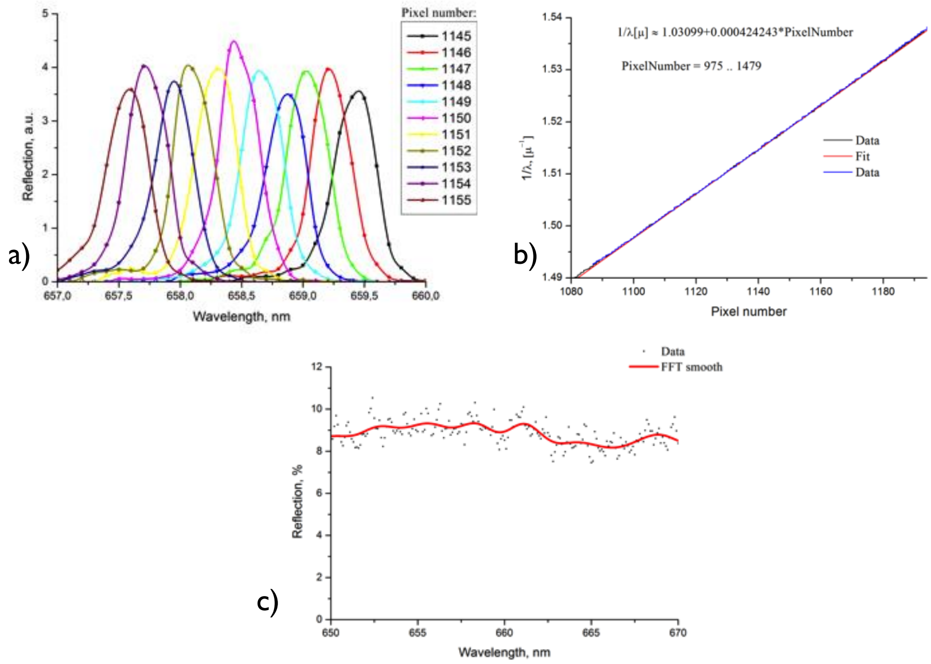

Figure 5: The spectral response of a 506 spectrometer chip, including a DPH and a RWG etched at the same level with a depth around 20 nm. The spectral range is 602-690 nm, the channel spectral spacing is 0.18 nm, and the pitch between adjacent output channels is 5.25 μm. The etching depth was 20 nm. a) the reflection from 10 adjacent channels ; b) dispersion curve c) reflection of the hologram. The testing laser bandwidth was 0.15 nm.

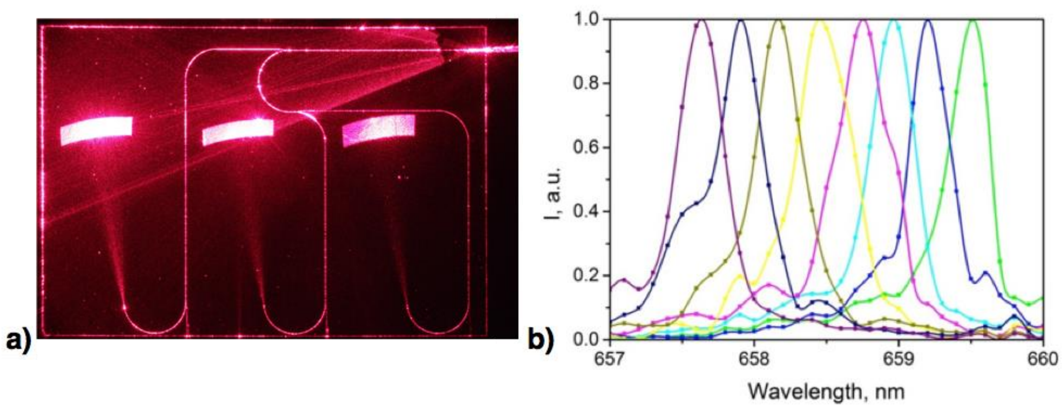

Figure 6: a) Optical top view photo of the chip illuminated by an input laser with a wavelength of 660 nm. b) Optical response to a tunable laser (FWHM = 0.2 nm).

III – Low-cost fabrication of photonic chips by nanoimprint lithography

A Step-and-Repeat NIL process was developed to replicate our spectrometer chips at a low cost. We developed a new NIL process by using an experimental NIL resist, mr-NIL 200, which is not sensitive to oxygen. Micro Resist Technology, a German manufacturer of resist materials (www.microresist.de), provided this experimental resist. A quartz mold was fabricated by electron beam lithography into an HSQ resist. The mold contains a spectrometer chip with 2 DPHs and a full optical circuitry. Imprints were done using the imprint tool Imprio 55 from Molecular Imprint. The chips were successfully replicated and measured (Fig. 7). Some small defects due to the imprint process (mainly breaks) can be observed on some chips, but the performance (DPH reflectivity, channel numbers, etc…) of the imprinted chips are very close to the ones made by EBL. **Around 100 chips were successfully imprinted with similar performances, and demonstrated the cost-effective fabrication of the nano-spectrometer chips.** aBeam Technologies has recently acquired its own imprint tool and is able to start small scale production if necessary.

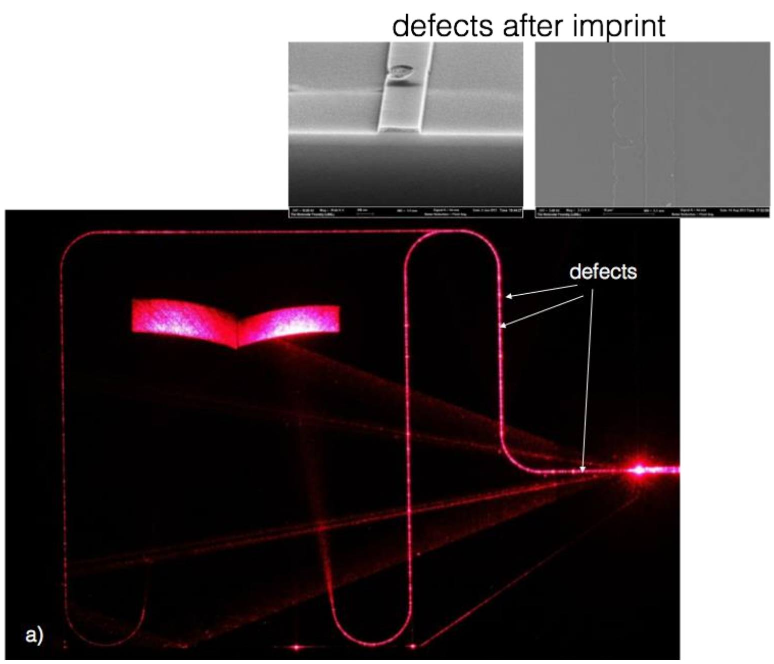

Figure 7: Imprinted DPH chip. Optical picture with a red laser input. Above: SEM pictures of defects due to imprinting.

IV – Optical validation of the devices and comparison to commercial systems

We have tested and characterized a few chips containing one or two planar holograms in detail and compared their performances to commercial systems.

As a typical example, the performance of an integrated spectrometer on chip composed of two parallel DPHs that are operating in adjacent spectral bands is presented in Figure 8. Each hologram covers a single spectral band (760–836 nm and 835–918 nm) with 542 channels, for a total of a 158 nm spectral range over 1084 channels and 0.15 nm channel spacing. An input spectral intensity as low as 50 pW/nm is sufficient for signal detection (3σ level) with an integration time of 10 ms. Figure 8b shows how the dispersion of channels along the output edge is linear in the wavenumber space for each DPH, with an accuracy better than 20% of the channel spacing. The spectral emission of a laser diode was measured by our spectrometer-on-chip and compared to the response from a bulky, commercially available spectrometer (Avantes-2048) that is widely used (see Figure 8a). Both spectrometers presented similar optical responses, validating our technology for spectroscopy-on-chips with numerous applications. **These results confirm the multiple advantages of our approach and present, to the best of our knowledge, the first demonstration and validation of a spectrometer-on-chip.**

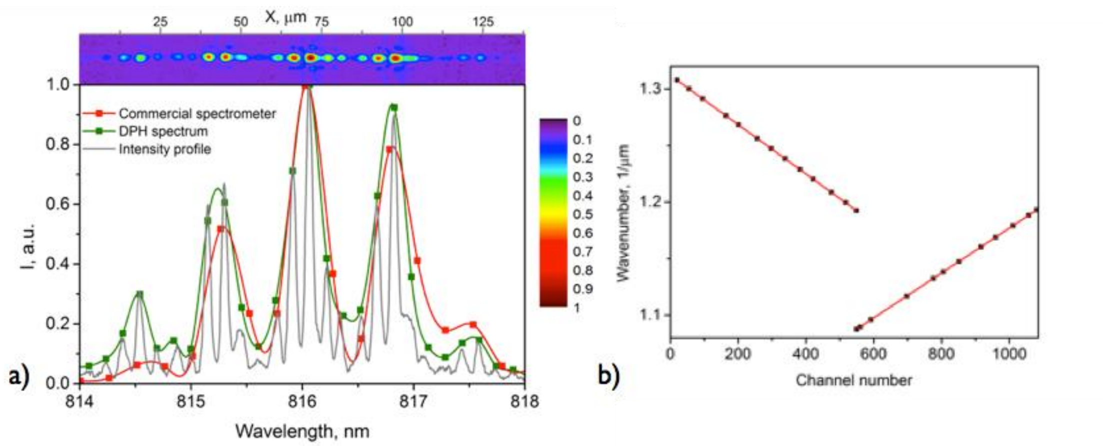

Figure 8: Validation of the spectrometer-on-chip. a) Comparison of optical responses of a 1084-channel spectrometer-on-chip, composed of two DPHs (with a bandwidth of 158 nm and spectral channel spacing of 0.15 nm) and a commercial spectrometer with a 0.4 nm resolution. b) Dispersion curve of the two-hologram spectrometer

V – Prototyping a whole spectrometer system into a small footprint package

The integration of the DPH chip with an input optical fiber and an electronic board (from the RGB laser) was successfully carried out. The general concept is presented in Figure 9. An optical fiber is aligned and glued to the input coupler and a CMOS linear sensor is glued to the output edge. This step requires high technical precision to align the DPH chip with the optical fiber. The software was provided by the RGB laser. Two prototypes have been assembled and tested (see section VII).

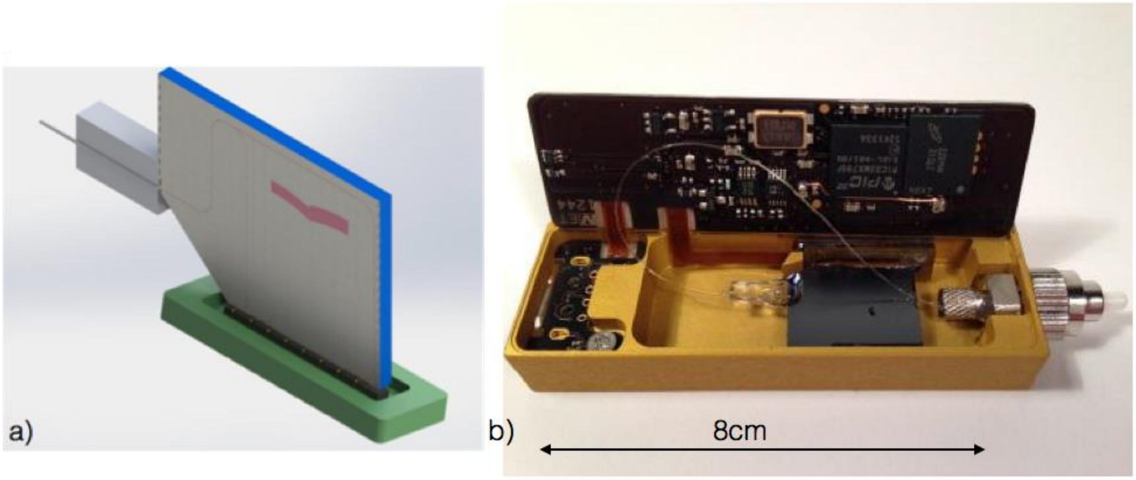

Figure 9: **USB key packaging.** a) general concept- the DPH spectrometer is attached to a CMOS linear array. b) optical picture of the electronic box provided by the RGB laser. A test chip has been aligned and glued to an input optical fiber and to a CMOS sensor.

VI – Novel concept of transmission on-chip spectrometer (CONFIDENTIAL)

A revolutionary approach of transmission on-chip spectrometers is an additional outcome of our STTR, and was not planned in the initial proposal. **The general concept of our "transmission" spectrometer is radically different from any other spectrometers with DPH chips** (Figure 10)**.** The core of our technology is a nanostructured film composed of photonic crystals, which allows the spectral information of the light to be extracted: each photonic crystal acts as a structural nano-filter, and the spectrum of the input light is reconstructed by analyzing the individual response of each PhCs. Our concept was first tested in optical free space. A few iterations of the design were implemented during the last months of our Phase II project and the first prototype to detect single wavelengths was assembled (Figure 11).

Our "transmission" spectrometer doesn't require any input optical fibers; it works with ambient light (high sensitivity) and can be integrated into small systems. The devices can be directly manufactured at low-cost and high-volume on top of commercial CMOS or CCD sensors. While planar photonic circuits are advantageous for lasing applications, a "transmission" spectrometer has a much larger field of applications and can potentially be integrated into cellular phone systems.

Our first prototype works with ambient light for single wavelength detection and is available for demonstration.

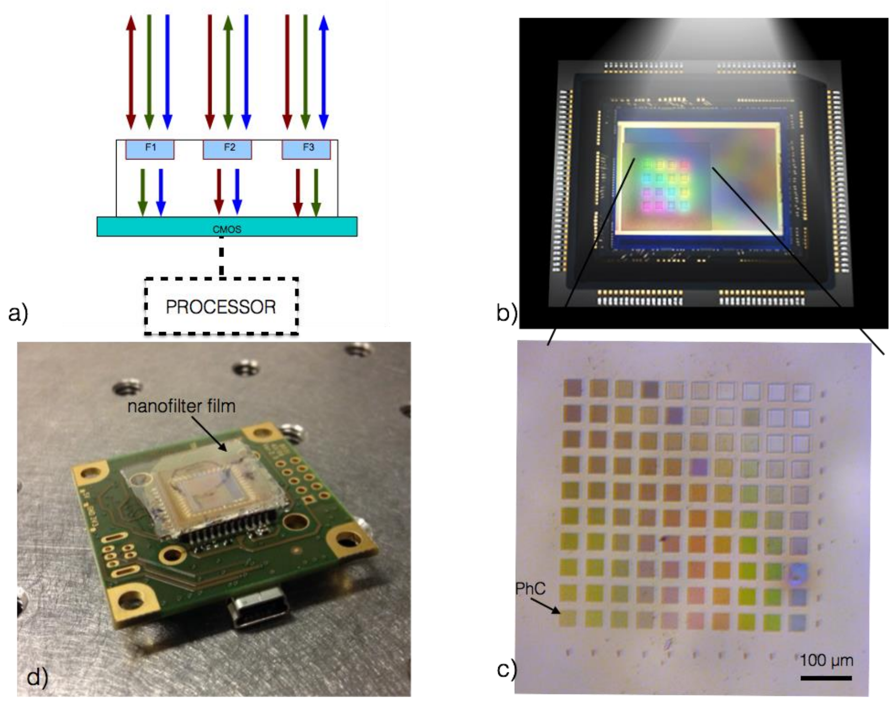

Figure 10: On-chip spectrometer based on structural nanofilters. a) the concept of the nanospectrometer, b) schematic view of its integration onto an image sensor. c) optical picture of a nanofilter with its structural color; d) a picture of a image sensor coupled with our nanostructured film.

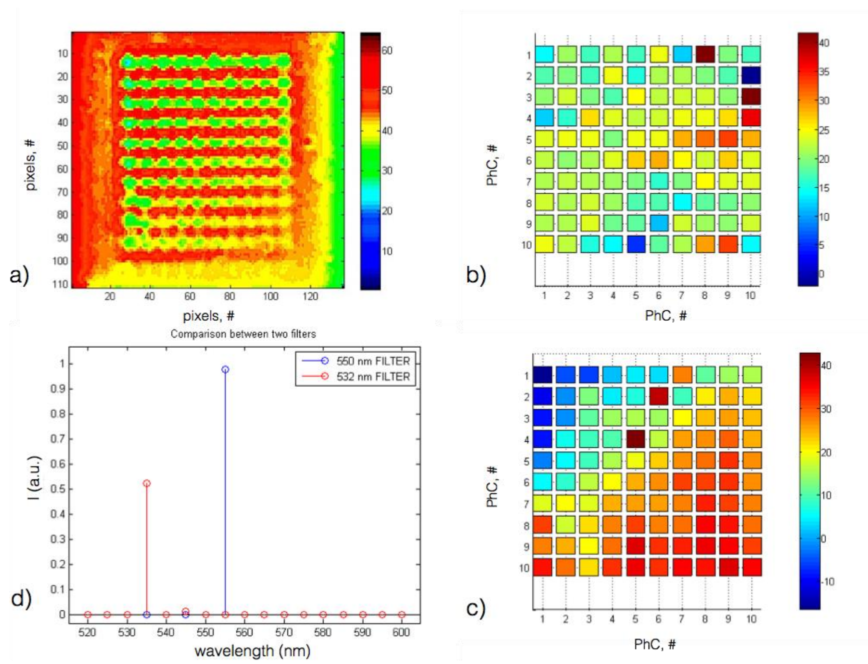

Figure 11: Single-Band Spectrometer prototype. a) intensity map onto CMOS sensor for an array of 100 photonic crystals (input light at λ=500 nm); b,c) map of the intensity extracted for each PhCs for λ=400 and 500 nm, respectively; d) example of the spectral response of our prototype to two input filtered lights.

VII – Prototypes delivered to US AFSOR

Three spectrometer prototypes have been assembled and are available for demonstration: two devices are based on DPH technology and one prototype uses nanofilters.

a) DPH spectrometer prototypes:

Both prototypes are composed of two planar holograms on one chip connected by a full optical circuitry and packed into a small package as shown in Figure 9b. The principal characteristics of the devices are summarized in the Table 1.

Name	Bandwidth (nm)	spectral resolution	minimum optical input
Prototype I	[624-687] & [770,853]	around 0.5 nm	>10 nW
Prototype II	[763,837] & [838,919]	<1 nm	>10 nW

Table 1: Principal optical characteristics of Prototype I and II.

Several optical measurements have been performed with multiple lasers and the response of our prototype has been compared with commercial bulky spectrometers from Avantes (Avantes-2048) and Ocean Optics (NIR-512). Figure 12 and 13 display the response of Prototype I for different conditions of light illumination through a single mode optical fiber. Prototype II works similarly to device 1, but presents a constant noise on the near IR range (838-919nm) due to a problem during the assembly of the prototype and a poor connection with the sensor recording the signal from the second DPHs (Figure 14).
Guidelines to use our prototype are provided in Annex I.

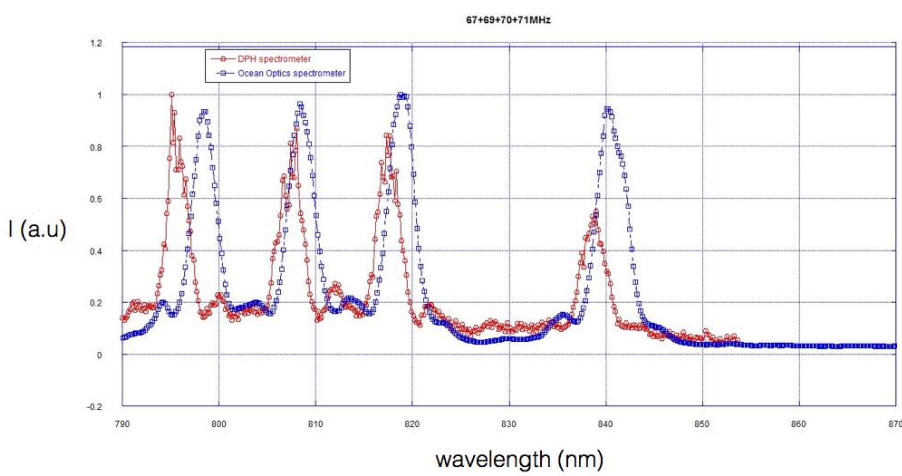

Figure 12: Response of Prototype I vs Ocean Optics Spectrometer to 4 lasers injected simultaneously.

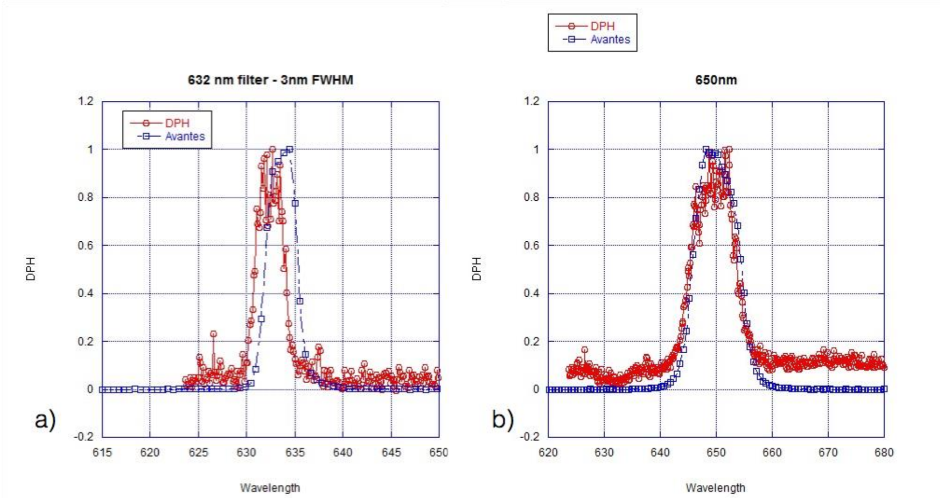

Figure 13: Response of Prototype I vs. Avantes spectrometer for a) 3nm and b) 10 nm FWHM input light.

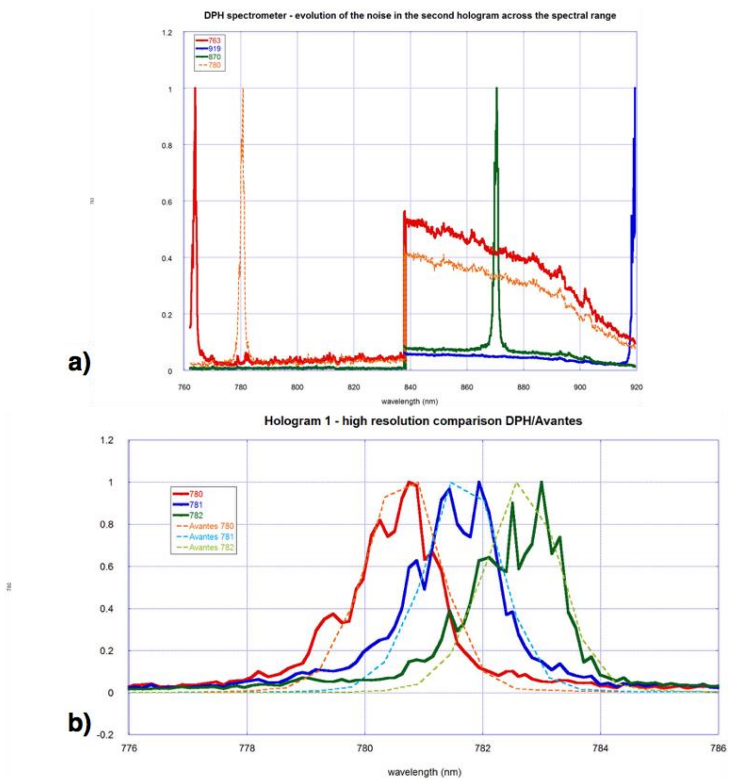

Figure 14: Prototype II. a) response to four different laser input signal =763,780,870,191 nm. The background noise on the second range of the spectrometer is clearly visible when the input light is centered onto the first spectral range (first DPH). b) comparison of Prototype II vs. Avantes spectrometer.

b) Transmission on-chip spectrometer prototype:

The first transmission-type on-chip spectrometer (Prototype 3) based on 150 nanofilters has been assembled on top of a commercial image sensor (Toshiba Teli BU 130) and is available for testing (Fig. 15a,b). The device allows for single wavelength values through a spectral range of 420 to 750 nm to be detected, and doesn't required any optical fibers, which offered a higher sensitivity. Figure 15c shows the response of our Prototype III vs a commercial spectrometer (Avantes 2048) to two laser signals with a wavelength shifted by 2 nm, demonstrating that the device is able of high spectral resolution.

Guidelines are provided in Annex II.

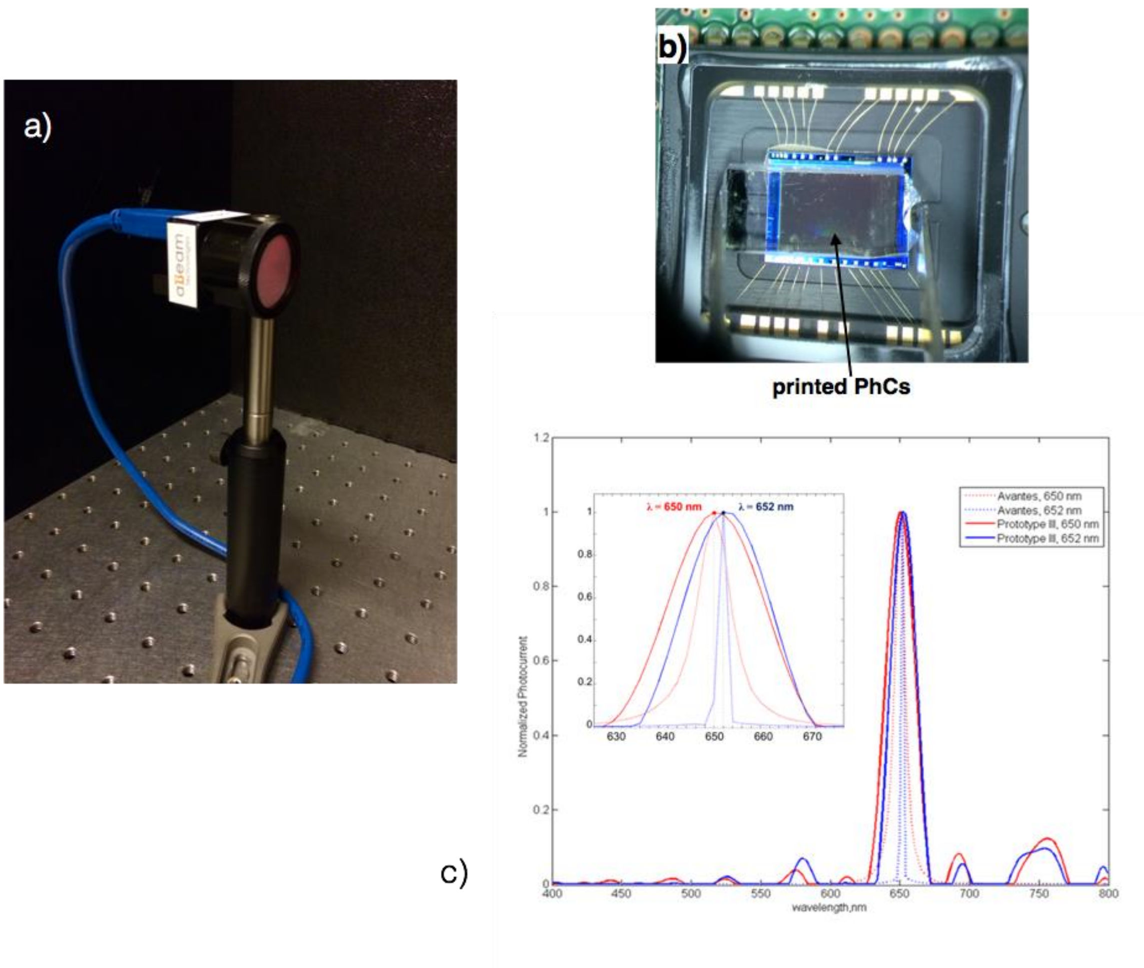

Figure 15: Prototype III. A,b) Picture of Prototype III and of the nanofilter film mounted on top of the sensor; c) response of Prototype III vs Avantes spectrometer to two different laser input signals, λ=650 and 652 nm.

VIII – Scientific Outcome of Phase II

Our work has been highly recognized by the scientific community through several publications (6 papers) and highlighted in the news, as well as oral presentations (10 talks) in international conferences and one record of invention for patent.

List of publications:

[1] Holographic Planar Lightwave Circuit for on-chip spectroscopy G. Calafiore, A. Koshelev, S. Dhuey, A. Goltsov, P. Sasorov, S. Babin, S. Cabrini, V. Yankov, C. Peroz ***Light : Science and Applications 3, e203 (2014)***

[2] Combination of a spectrometer-on-chip and an array of Young's interferometers for laser spectrum monitoring A. Koshelev, G. Calafiore, S. Dhuey, A. Goltsov, P. Sasorov, S. Babin, S. Cabrini, V. Yankov, C. Peroz ***Optics Letters 39, 5645 (2014)***

[3] Multiband wavelength demultiplexer based on digital planar holography for on-chip spectroscopy applications C. Peroz, C. Calo, A. Goltsov, S. Dhuey, A. Koshelev, P. Sasorov, I. Ivonin, S. Babin, S. Cabrini, and V. Yankov, ***Optics Letters 37, 695 (2012)***

[4] Fabrication of digital planar holograms into high refractive index waveguide core for spectroscopy-on-chip applications C. Calò, V. Lacatena, A. Koshelev, S. Dhuey, I. Ivonin, S. Babin, A. Goltsov, S. Cabrini, V. Yankov, C. Peroz, ***J. Vac. Sci. Technol B. 30, 2166 (2012)***

Research Highlight in JVSTB: Beam Me Out, Scotty: Making an Improved Holographic Lab on a Chip Spectrometer

[5] High-Resolution Spectrometer-on-Chip Based on Digital Planar Holography, C. Peroz, A. Goltsov, S. Dhuey, P. Sasorov, I. Ivonin, B. Harteneck, S. Kopyatev, S. Cabrini, S. Babin, V. Yankov, ***IEEE Photonics Journal 3, 888 (2011).***

[6] Digital Planar Holographic spectrometer-on-chip fabricated by Step and Repeat UV nanoimprint lithography on pre-spin coated films, C. Peroz, S. Dhuey, A. Goltsov, M. Volger, B. Harteneck, S. Kopyatev, S. Cabrini, S. Babin, V. Yankov ***Micro. Elect. Eng. 88, 2092 (2011)***.

In preparation :

Fabrication of planar lightwave circuits for on-chip spectroscopy by Step and Repeat UV NanoImprint Lithography G. Calafiore, A. Koshelev, S. Dhuey, C. Piña-Hernandez, S. Sassolini, M. Vogler, A. Goltsov, F.C. Pirri, V. Yankov, S. Cabrini, C. Peroz **to be submitted to JVSTB**

ANNEX I

GUIDELINES TO USE PROTOTYPE 1 AND 2

1. Go to http://www.rgb-laser.com/
2. On the upper menu bar, click on download, then on software.
3. Download **Waves spectroscopy application software V1.7.2** and install it.
4. Connect the spectrometer to a single mode optical fiber.
5. Connect the DPH spectrometer, configured just as in Figure 1, to any USB2.0 port of your computer.

Figure 1 - DPH spectrometer connected to a SM fiber and mini-USB cable

6. Allow some time for the driver installation.
7. Start “Waves”. If you are asked to choose between “Simulated spectrometer” and another choice, pick the latter.
8. An interface like the one in Figure 2 should appear on your screen.
9. Set the exposure time either to automatic or manual by using the pop-up menu in D. If the manual option is selected, adjust the exposure time from the prompt “Time” next to D. If automatic mode is selected, go to step 12.
10. Set a fairly high number of frames to compensate for the white noise.
11. To calibrate the exposure time manually, start the measurement by clicking on B.
12. Once you have adjusted the exposure time and number of frames, turn off your light source and record the dark spectrum by clicking on F. Now run a measurement without the dark spectrum by clicking on G.
13. Start measurement: click A or B for single or continuous measurements, respectively.
14. Use the complementary panels (i.e. H) to get the desired visualization.
15. Click C to stop the measurement.
16. To save the raw data of your spectrum click on File > Save Spectrum As. You can also export the graph as it is visualized by clicking on File > Export diagram.
17. The software will also identify peaks and FWHM. You can record and store them in the “Spectra” panel.

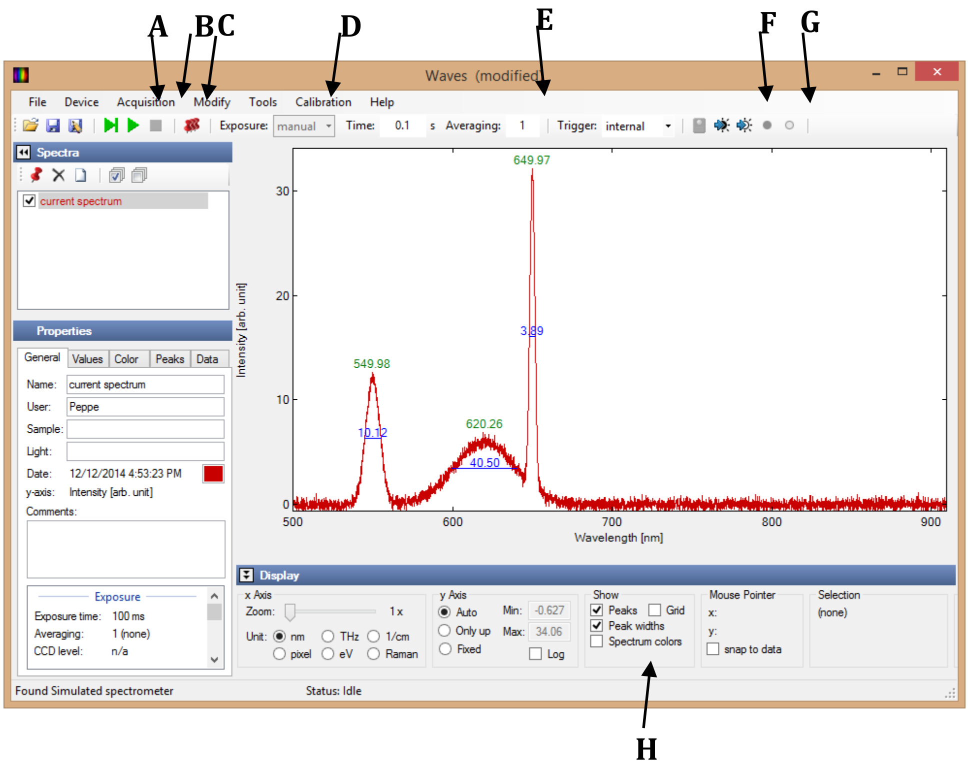

Figure 2 - Layout of the Interface for DPH spectrometers

ANNEXE II

GUIDELINES TO USE PROTOTYPE 3

If necessary, aBeam Tech. can provide a computer with all the required drivers and software for a period of two weeks.

1. Optical setup preparation

The suggested setup to run a measurement with Prototype III is shown in Figure 1. The length f_c has to be adjusted to have the collimated light exiting the lens. Light is filtered and sent to the device. Note that if the setup is correctly arranged, the length *d* in Figure 1 can be varied without affecting the spectral measurement. If a laser source is used, the beam has to be opened to reach the size of the prototype's aperture. Then it has to be collimated by a second lens in order to measure 1-inch size across.
Measurements have to be performed in darkness to avoid noisy measurements. If a dim ambient light is present, it can be filtered by dark spectrum removal – as described in paragraph 5 – as long as it is less intense than the light that is to be measured.

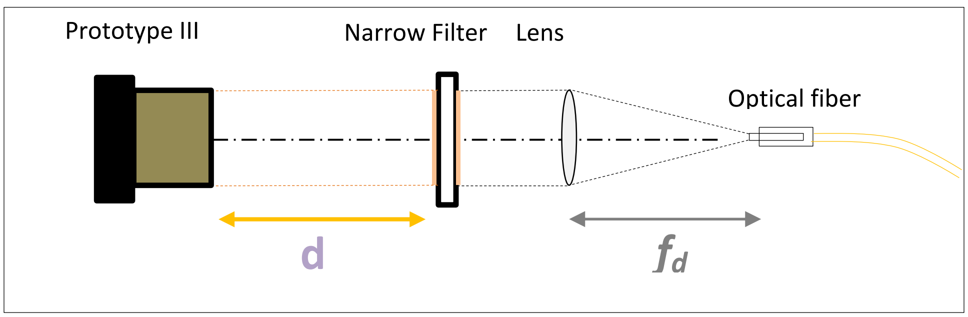

Figure 1 -Sketch of the suggested optical setup to test Prototype III.

2. Program and System requirements for Graphic User Interface (GUI)

System:

- ✓ One USB 3.0 enabled port
- ✓ Operative System: Windows XP, x64, or higher (the code does not work on a MAC)
- ✓ CPU @ 2.7GHz dual core or higher
- ✓ RAM: 4Gb minimum are recommended

Programs:

- ✓ MATLAB R2013a or newer. The program has to include at least the Image Acquisition and Image Processing toolboxes. A trial version can be downloaded here:

https://www.mathworks.com/programs/trials/trial_request.html?eventid=492862641&s_iid=coabt_trial_abtus_bod

✓ ActiveUSB from A&b software. A trial of ActiveUSB can be download and used for 30 days from: http://www.ab-soft.com/download/ActiveUSBSetup.exe

3. Installation of Active USB

- Run ActiveUSBSetup.
- Select "Basic" from the installation options.
- Click on SDK and Applications in the window that will appear next.
- Once the installation is complete, restart your computer.
- Connect the prototype to the provided USB cable to a USB3.0 port.
- Check the status LED on the back of the camera. A slowly blinking green light indicates that the camera is correctly connected.
- Go to C:\ProgramFiles\ActiveUSB and click UcamConfig.exe on .. A window will open that displays the status of the driver. Check that the Camera is visualized with the name of "Toshiba-Teli BU130C" and that the compliant driver is installed. If not, check the box next to "Install" and click Run.
- To check whether the camera is set and ready for the acquisition, go to the device manager in the control panel and make sure that the camera appears under the Imaging Devices entry.

4. Graphic User Interface

Graphic User Interface of the prototype runs in MATLAB and needs a proprietary script along with some data files. To request these files, contact aBeam Technologies Inc.
The interface is described below and refers to Figure 8:

A) Continuous measurement button;
B) Play and Pause: single measurement button;
C) Stop any spectral measurement;
D) Dark spectrum measurement;
E) If checked, the dark spectrum is subtracted from the ongoing measurement;
F) Waitbar, indicates the progress of the measurement;
G) Auto-scale, if checked the spectrum is scaled automatically, otherwise the user indicates the max value of the y-axis in the prompt below;
H) Smoothening values. Optimal levels are between -0.4 and -2. Lower values give cleaner measurements but decrease the resolution;
I) Number of frames to average. In high quality measurements, this value always has to be set greater than 10;
J) This bar guides the user to the optimal exposure level, thus more reliable spectral measurements. Before running a measurement, make sure the bar is green;
K) Coarse exposure time regulator;

L) Exposure time;
M) Menu bar. It only contains two entries: *save spectral data* and *save image*. The first allows the user to save the spectral raw data in a 201x1 vector, whereas the second option returns the screenshot of the GUI.

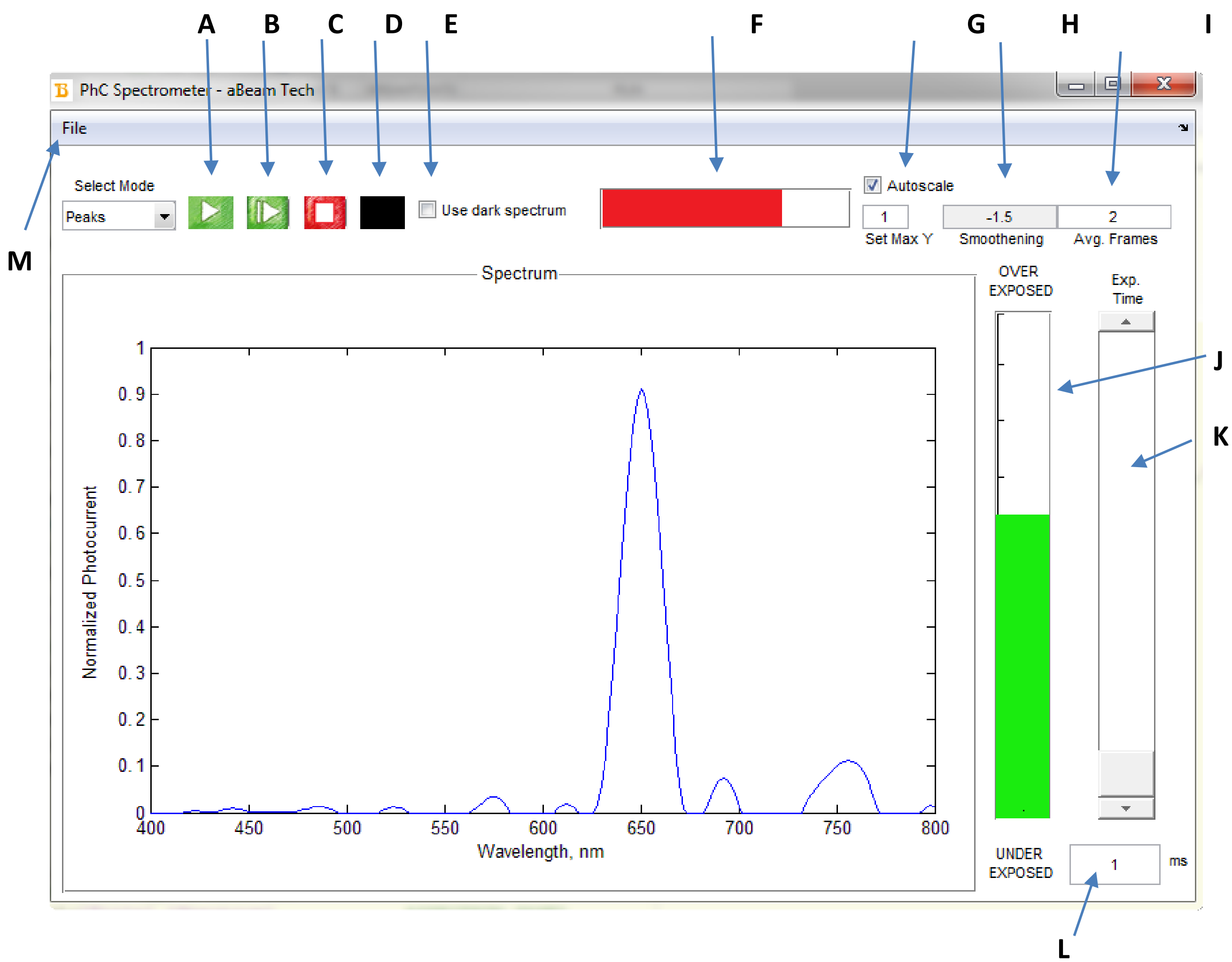

Figure 2 - Prototype III, Graphic User Interface

To run a measurement through the GUI, follow the following steps:

1) Arrange the prototype to adhere to the setup as described in paragraph 1.
2) Make sure you followed all the steps reported in paragraph 3 to interface the device with the computer.
3) Ensure the LED status in the camera is green and is blinking slowly.
4) In Matlab, Open and Run the script provided by aBeam Technologies Inc. by clicking on the RUN button in the upper bar.
5) If an error appears in the command window, refer to paragraph 5 to troubleshoot the issue.

6) If everything is correctly set, the interface shown in Figure 2 will appear. **Lower the ambient light to the dimmest level possible and turn on the light source to begin the measurement.**
7) Bring the exposure bar (J) to green by adjusting the exposure time (K and L).
8) Turn off the light source to measure. The exposure bar will turn red.
9) Increase the number of frames to average to 10 or more (I).
10) Click on the dark spectrum button to record the dark spectrum.
11) Wait for the spectrum to be recorded and displayed.
12) Check the “remove Dark Spectrum” box (E).
13) Turn on the light source to measure.
14) Keep both the exposure time and averaged frames unaltered.
15) Run continuous measurements by clicking on A, or individual single measurements by clicking on B.
16) The light source spectrum will be displayed in the central panel.
17) If you want to save the 201 spectral samples (400:2:800 nm), click on Menu (M) and “Save Spectral Data”.
18) If you want to save the GUI window with the image of the spectrum, click on Menu (M) and “Save Image”.
19) Click on Stop (C) to stop the scanning, close the GUI window and Matlab to shut down the GUI.

1.

1. Report Type

Final Report

Primary Contact E-mail

Contact email if there is a problem with the report.

sb@abeamtech.com

Primary Contact Phone Number

Contact phone number if there is a problem with the report

5104156032

Organization / Institution name

Abeam Technologies, Inc.

Grant/Contract Title

The full title of the funded effort.

HIGH-RESOLUTION, LOW-COST SPECTROMETERS-ON-CHIP

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-C-0077

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Dr. C. Peroz

Program Manager

The AFOSR Program Manager currently assigned to the award

Dr. Gernot Pomrenke

Reporting Period Start Date

09/30/2012

Reporting Period End Date

09/29/2014

Abstract

A novel class of low-cost and high resolution spectrometer-on-chips has been developed that are suitable for numerous laser-monitoring applications. The technology is based on the integration of digital planar holograms and a full optical circuitry on the same photonic chip. The prototypes are fabricated at a low-cost by nanoimprint lithography and are packed into the size of a USB key. Nano-spectrometers with a resolution down to 0.5 nm and a spectral range up to 229 nm were successfully demonstrated. The original concept of an on-chip spectrometer integrated into commercial image sensors was demonstrated and opens the route to numerous applications. Our miniaturized spectrometers are defining the state-of-the-art for on-chip spectroscopy, as well as in terms of spectral resolution and bandwidth than for their miniaturized size.

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

sf_298_aBeam.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

Final_Report_v3a.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

[1] Holographic Planar Lightwave Circuit for on-chip spectroscopy G. Calafiore, A. Koshelev, S. Dhuey, A. Goltsov, P. Sasorov, S. Babin, S. Cabrini, V. Yankov, C. Peroz Light : Science and Applications 3, e203 (2014)
[2] Combination of a spectrometer-on-chip and an array of Young's interferometers for laser spectrum monitoring A. Koshelev, G. Calafiore, S. Dhuey, A. Goltsov, P. Sasorov, S. Babin, S. Cabrini, V. Yankov, C. Peroz Optics Letters 39, 5645 (2014)
[3] Multiband wavelength demultiplexer based on digital planar holography for on-chip spectroscopy applications C. Peroz, C. Calo, A. Goltsov, S. Dhuey, A. Koshelev, P. Sasorov, I. Ivonin, S. Babin, S. Cabrini, and V. Yankov, Optics Letters 37, 695 (2012)
[4] Fabrication of digital planar holograms into high refractive index waveguide core for spectroscopy-on-chip applications C. Calò, V. Lacatena, A. Koshelev, S. Dhuey, I. Ivonin, S. Babin, A. Goltsov, S. Cabrini, V. Yankov, C. Peroz, J. Vac. Sci. Technol B. 30, 2166 (2012)
Research Highlight in JVSTB: Beam Me Out, Scotty: Making an Improved Holographic Lab on a Chip Spectrometer
[5] High-Resolution Spectrometer-on-Chip Based on Digital Planar Holography, C. Peroz, A. Goltsov, S. Dhuey, P. Sasorov, I. Ivonin, B. Harteneck, S. Kopyatev, S. Cabrini, S. Babin, V. Yankov, IEEE Photonics Journal 3, 888 (2011).
[6] Digital Planar Holographic spectrometer-on-chip fabricated by Step and Repeat UV nanoimprint lithography on pre-spin coated films, C. Peroz, S. Dhuey, A. Goltsov, M. Volger, B. Harteneck, S. Kopyatev, S. Cabrini, S. Babin, V. Yankov Micro. Elect. Eng. 88, 2092 (2011).
In preparation:
Fabrication of planar lightwave circuits for on-chip spectroscopy by Step and Repeat UV NanoImprint Lithography G. Calafiore, A. Koshelev, S. Dhuey, C. Piña-Hernandez, S. Sassolini, M. Vogler, A. Goltsov, F.C. Pirri, V. Yankov, S. Cabrini, C. Peroz to be submitted to JVSTB

Changes in research objectives (if any):

The objectives were completed. In addition, at the end of the project, a very new concept of spectrometer-on-chip was explored, utilizing light transmission principle.

Change in AFOSR Program Manager, if any:

Initial manager: Dr. Brian Thomas (very short time)

Extensions granted or milestones slipped, if any:

No slipped milestone, the project was perfectly on schedule.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Dec 28, 2014 00:15:05 Success: Email Sent to: sb@abeamtech.com